C++ Smart Pointers

CSE 333 Fall 2023

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Relevant Course Information

- Exercise 8 due tonight by 10pm (11/6)

- Exercise 9 released tomorrow and due next Wed (11/15)
  - Practice using C++ smart pointers (this lecture), inheritance (next lecture)

- HW 3 due Nov. 23
  - *Don't delay!!!*

- No lecture this Friday (11/10; Veterans Day)

Lecture Outline

- **Introducing STL Smart Pointers**
  - `std::shared_ptr`
  - `std::unique_ptr`
- Smart Pointer Limitations
  - `std::weak_ptr`

Goals for Smart Pointers

- Should automatically handle dynamically-allocated memory to decrease programming overhead of managing memory
  - Don’t have to explicitly call `delete` or `delete[]`
  - Memory will deallocate when no longer in use – ties the lifetime of the data to the smart pointer object

- Should work similarly to using a normal/“raw” pointer
  - Expected/usual behavior using `->`, `*`, and `[]` operators
  - Only declaration/construction should be different

Example: ToyPtr Class Template

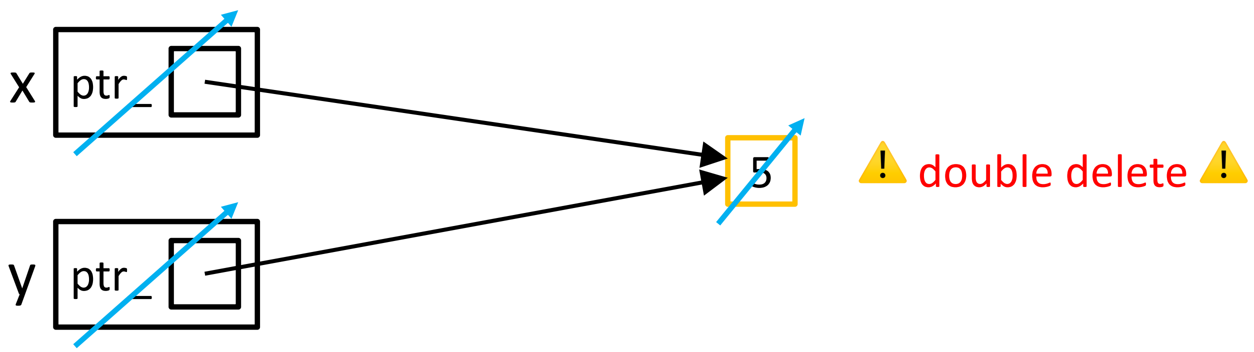
ToyPtr.h

```
#ifndef TOYPTR_H_
#define TOYPTR_H_

template <typename T>
class ToyPtr {
 public:
  ToyPtr(T* ptr) : ptr_(ptr) { }     // constructor
  ~ToyPtr() { delete ptr_; }         // destructor


  T& operator*() { return *ptr_; }   // * operator
  T* operator->() { return ptr_; }   // -> operator

 private:
  T* ptr_;                          // the pointer itself
};

#endif  // TOYPTR_H_
```

ToyPtr Class Issue

toyuse.cc

```
#include "ToyPtr.h"

// We want two pointers!
int main(int argc, char** argv) {
  ToyPtr<int> x(new int(5));
  ToyPtr<int> y(x);
  return EXIT_SUCCESS;
}
```



Brainstorm ways to design around this. 🤔💭

Smart Pointers Solutions

- Option 1: **Reference Counting**
  - `shared_ptr` (and `weak_ptr`)
  - Track the number of references to an "owned" piece of data and only deallocate when no smart pointers are managing that data
- Option 2: **Unique Ownership of Memory**
  - `unique_ptr`
  - Disable copying (cctor, op=) to prevent sharing

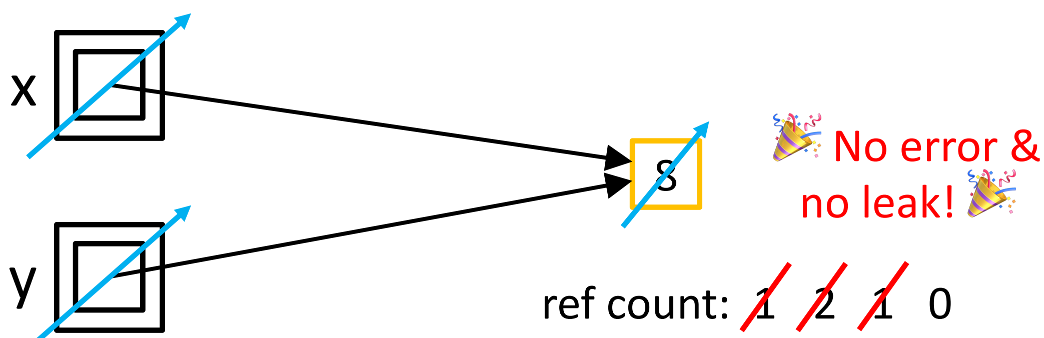
Option 1: Reference Counting

- `shared_ptr` implements **reference counting**
  - https://cplusplus.com/reference/memory/shared_ptr/
  - Counts the number of references to a piece of heap-allocated data and only deallocates it when the reference count reaches 0
    - This means that it is no longer being used and its lifetime has come to an end
  - Managed abstractly through sharing a *resource counter*:
    - Constructors will **create** the counter
    - Copy constructor and operator= will **increment** the counter
    - Destructor will **decrement** the counter

Now using `shared_ptr`

shareduse.cc

```
#include <memory>    // for std::shared_ptr
#include <cstdlib>   // for EXIT_SUCCESS

// We want two pointers!
int main(int argc, char** argv) {
  std::shared_ptr<int> x(new int(5));  // creates ref count
  *x += 3;                             // usage is the same
  std::shared_ptr<int> y(x);           // increments ref count
  return EXIT_SUCCESS;
}
```

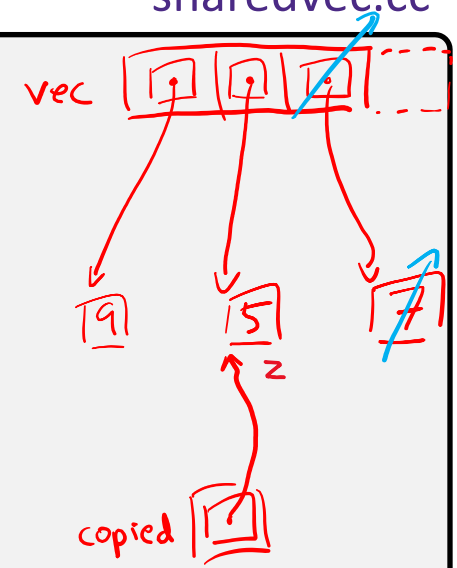


`shared_ptr`s and STL Containers

- Use `shared_ptr`s inside STL Containers
  - Avoid extra object copies
  - Safe to do, since copy/assign maintain a shared reference count
    - Copying increments ref count, then original is destructed

sharedvec.cc

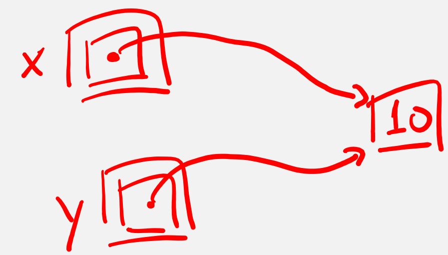
```
vector<std::shared_ptr<int> > vec;

vec.push_back(std::shared_ptr<int>(new int(9)));
vec.push_back(std::shared_ptr<int>(new int(5)));
vec.push_back(std::shared_ptr<int>(new int(7)));

int& z = *vec[1];
std::cout << "z is: " << z << std::endl;

std::shared_ptr<int> copied(vec[1]);  // works!
std::cout << "*copied: " << *copied << std::endl;

vec.pop_back(); // removes smart ptr & deallocates 7!
```



Practice with Reference Counts

- What is the expected output of this program?
  - `use_count()` – returns reference count
  - `unique()` – returns ref count == 1 (`bool`)

sharedrefcount.cc




```
... // the necessary includes are here

int main(int argc, char** argv) {
  std::shared_ptr<int> x(new int(10));
  std::cout << x.use_count() << std::endl;  // 1

  // temporary inner scope (!)
  {
    std::shared_ptr<int> y(x);
    std::cout << y.use_count() << std::endl;  //2
  }  // y is destructed here!
  std::cout << x.use_count() << std::endl;  // 1
  std::cout << x.unique() << std::endl;  // true

  return EXIT_SUCCESS;  // x is destructed here (10 is cleaned up)
}
```

Option 2: Unique Ownership

- A `unique_ptr` is the *sole owner* of a pointer to memory
  - https://cplusplus.com/reference/memory/unique_ptr/
  - Enforces uniqueness by disabling copy and assignment (compiler error if these methods are used)
    - Will therefore *always* call `delete` on the managed pointer when destructed
  - As the sole owner, a `unique_ptr` can choose to *transfer* or *release* ownership of a pointer

unique_ptrs Cannot Be Copied

- std::unique_ptr has disabled its copy constructor and assignment operator
  - You cannot copy a unique_ptr, helping maintain "uniqueness" or "ownership"

uniquefail.cc

```
#include <memory>   // for std::unique_ptr
#include <cstdlib>  // for EXIT_SUCCESS

int main(int argc, char** argv) {
  std::unique_ptr<int> x(new int(5));  // 1-arg ctor (pointer)            ✓

  std::unique_ptr<int> y(x);           // cctor disabled; compiler error  ✗

  std::unique_ptr<int> z;              // default ctor, holds nullptr     ✓

  z = x;                               // op= disabled; compiler error    ✗

  return EXIT_SUCCESS;
}
```

`unique_ptr`s and STL

- `unique_ptr`s *can* also be stored in STL containers!
  - Contradiction? STL containers make copies of stored objects and `unique_ptr`s cannot be copied…

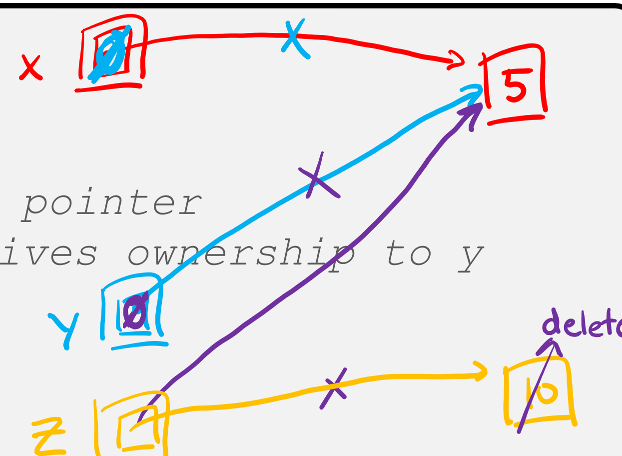
- Recall: *why* do container operations/methods create extra copies?
  - Generally to **move** things around in memory/the data structure
  - The end result is still one copy of each element – this doesn't break the sole ownership notion!

Passing Ownership

- As the "owner" of a pointer, `unique_ptr`s should be able to remove or transfer its ownership
  - `release()` and `reset()` free ownership

uniquepass.cc

```
int main(int argc, char** argv) {
1 unique_ptr<int> x(new int(5));
  cout << "x: " << *x << endl;
  // Releases ownership and returns a raw pointer
2 unique_ptr<int> y(x.release());  // x gives ownership to y
  cout << "y: " << *y << endl;

3 unique_ptr<int> z(new int(10));
  // y gives ownership to z
  // z's reset() deallocates "10" and stores y's pointer
4 z.reset(y.release());
  return EXIT_SUCCESS;
}
```



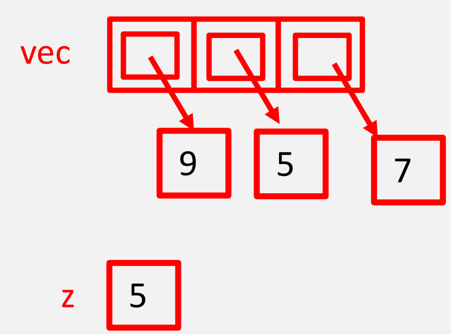
`unique_ptr` and STL Example

- STL's supports transfer ownership of `unique_ptr`s using **move** semantics

uniquevec.cc

```
int main(int argc, char** argv) {
  std::vector<std::unique_ptr<int> > vec;

  vec.push_back(std::unique_ptr<int>(new int(9)));
  vec.push_back(std::unique_ptr<int>(new int(5)));
  vec.push_back(std::unique_ptr<int>(new int(7)));

  // z holds 5
  int z = *vec[1];
  std::cout << "z is: " << z << std::endl;

  // compiler error!
  std::unique_ptr<int> copied(vec[1]);

  return EXIT_SUCCESS;
}
```

moves instead of copying when capacity is increased



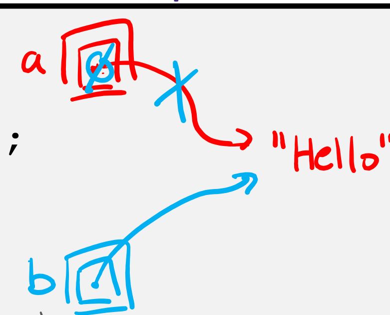
See full lecture code of uniquevec.cc!

unique_ptr and Move Semantics

- "Move semantics" (as compared to "Copy semantics") move values from one object to another without copying
  - https://cplusplus.com/doc/tutorial/classes2/#move
  - Useful for optimizing away temporary copies
  - STL's use move semantics to transfer ownership of unique_ptrs instead of copying

uniquemove.cc

```
... (includes and other examples)
int main(int argc, char** argv) {
  std::unique_ptr<string> a(new string("Hello"));

  // moves a to b
  std::unique_ptr<string> b = std::move(a);
  // a is now nullptr (default ctor of unique_ptr)
  std::cout << "b: " << *b << std::endl; // "Hello"

  return EXIT_SUCCESS;
}
```



Aside: Smart Pointers and Arrays

- Smart pointers can store arrays as well and will call `delete[]` on destruction

uniquearray.cc

```
#include <memory>    // for std::unique_ptr
#include <cstdlib>   // for EXIT_SUCCESS

using std::unique_ptr;

int main(int argc, char **argv) {
  unique_ptr<int[]> x(new int[5]);

  x[0] = 1;
  x[2] = 2;

  return EXIT_SUCCESS;
}
```

Choosing Between Smart Pointers

- `unique_ptr`s make ownership very clear
  - Generally the default choice due to reduced complexity – the owner is responsible for cleaning up the resource
    - Example: would make sense in HW1 & HW2, where we specifically documented who takes ownership of a resource
  - Less overhead: small and efficient

- `shared_ptr`s allow for multiple simultaneous owners
  - Reference counting allows for “smarter” deallocation but consumes more space and logic and is trickier to get right
  - Common when using more “well-connected” data structures

Lecture Outline

- Introducing STL Smart Pointers
  - `std::shared_ptr`
  - `std::unique_ptr`
- **Smart Pointer Limitations**
  - `std::weak_ptr`

Limitations with Smart Pointers

- Smart pointers are only as "smart" as the behaviors that have been built into their class methods and non-member functions!

- Limitations we will look at now:
  - Can't tell if pointer is to the heap or not
  - Circumventing ownership rules
  - Still possible to leak memory!
  - Sorting smart pointers *[Bonus slides]*

Using a Non-Heap Pointer

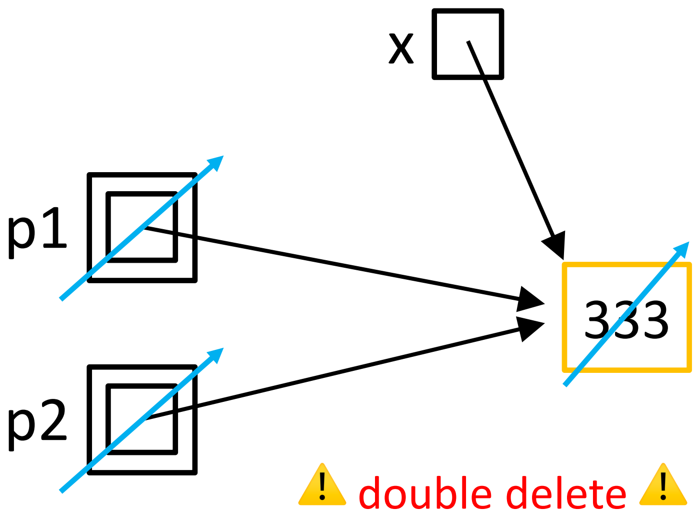
- Smart pointers will still call `delete` when destructed

```
#include <cstdlib>
#include <memory>

using std::shared_ptr;

int main(int argc, char** argv) {
  int x = 333;

  shared_ptr<int> p1(&x);

  return EXIT_SUCCESS;
} // invalid delete on destruction!
```

Re-using a Raw Pointer (unique_ptr)

- Smart pointers can't tell if you are re-using a raw pointer

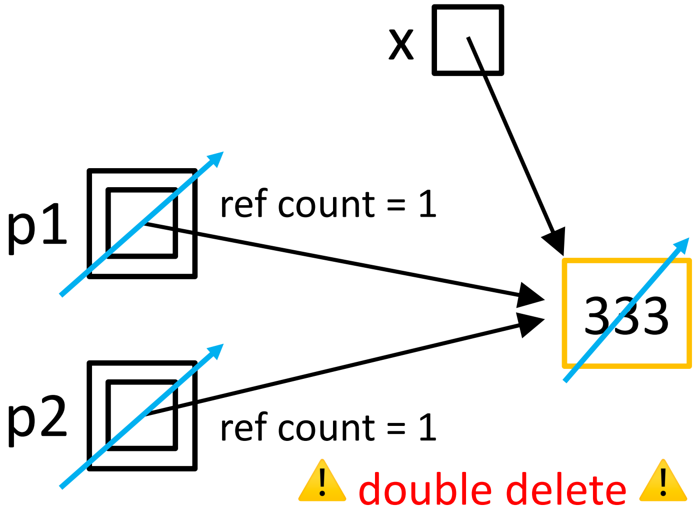
```
#include <cstdlib>
#include <memory>

using std::unique_ptr;

int main(int argc, char** argv) {
  int* x = new int(333);

  unique_ptr<int> p1(x);

  unique_ptr<int> p2(x);

  return EXIT_SUCCESS;
}
```



Re-using a Raw Pointer (`shared_ptr`)

- Smart pointers can't tell if you are re-using a raw pointer

```
#include <cstdlib>
#include <memory>

using std::shared_ptr;

int main(int argc, char** argv) {
  int* x = new int(333);

  shared_ptr<int> p1(x);

  shared_ptr<int> p2(x);

  return EXIT_SUCCESS;
}
```



Solution: Don't Use Raw Pointer Variables

- Smart pointers replace your raw pointers; passing `new` and then using the copy constructor is safer:

```
#include <cstdlib>
#include <memory>

using std::shared_ptr;

int main(int argc, char** argv) {
  int* x = new int(333);

  shared_ptr<int> p1(new int(333));

  shared_ptr<int> p2(p1);

  return EXIT_SUCCESS;
}
```

Caution Using get()

- Smart pointers still have functions to return the raw pointer without losing its ownership
  - get() can circumvent ownership rules!

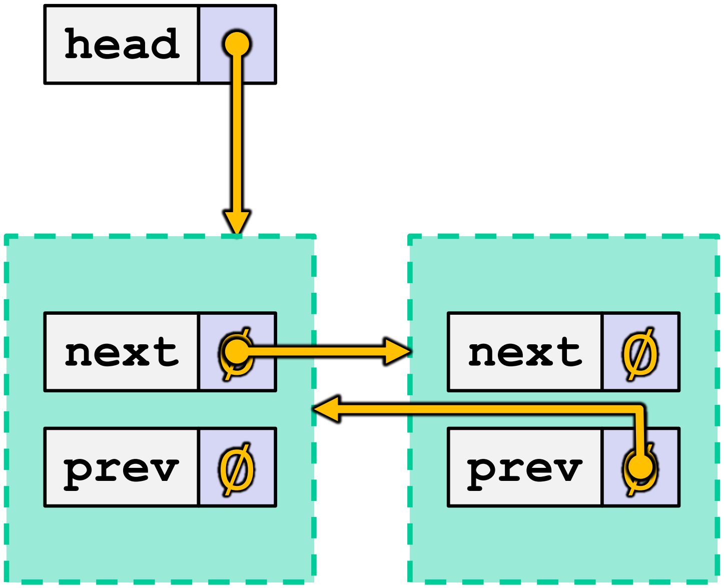
```
#include <cstdlib>
#include <memory>

// Same as re-using a raw pointer
int main(int argc, char** argv) {

  unique_ptr<int> p1(new int(5));

  unique_ptr<int> p2(p1.get());

  return EXIT_SUCCESS;
}
```

Cycle of `shared_ptr`s

- What happens when `main` returns?

memory leak!
nodes not deallocated

```
#include <cstdlib>
#include <memory>

using std::shared_ptr;

struct A {
  shared_ptr<A> next;
  shared_ptr<A> prev;
};

int main(int argc, char** argv) {
  shared_ptr<A> head(new A());
  head->next = shared_ptr<A>(new A());
  head->next->prev = head;

  return EXIT_SUCCESS;
}
```



sharedcycle.cc

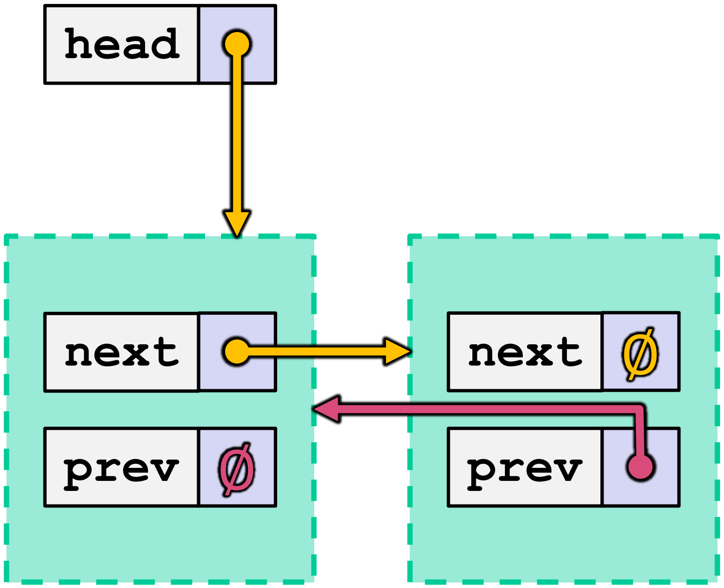
Solution: `weak_ptr`s

- `weak_ptr` is similar to a `shared_ptr` but *doesn't affect* the reference count
  - https://cplusplus.com/reference/memory/weak_ptr/
  - Not really a pointer as it **cannot be dereferenced** (!) – would break our notion of shared ownership
    - To deference, you first use the **`lock`** method to get an associated `shared_ptr`

Breaking the Cycle with `weak_ptr`

- Now what happens when `main` returns? No memory leak!

```
#include <cstdlib>
#include <memory>

using std::shared_ptr;
using std::weak_ptr;

struct A {
  shared_ptr<A> next;
  weak_ptr<A> prev;
};

int main(int argc, char** argv) {
  shared_ptr<A> head(new A());
  head->next = shared_ptr<A>(new A());
  head->next->prev = head;

  return EXIT_SUCCESS;
}
```



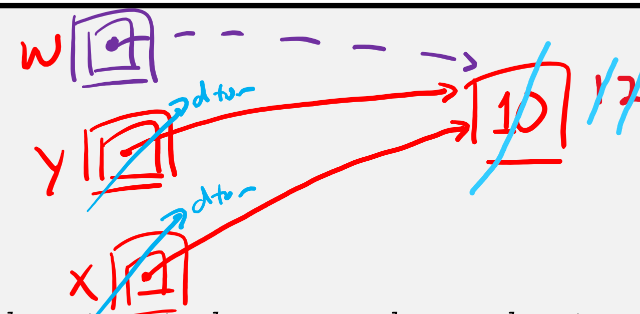
weakcycle.cc

Dangling `weak_ptr`s

- `weak_ptr`s don't change reference count and can become "*dangling*"
  - Data referenced may have been `delete`'d

weakrefcount.cc

```
... (includes and other examples)
int main(int argc, char** argv) {
  std::weak_ptr<int> w;

  {  // temporary inner scope
    std::shared_ptr<int> y(new int(10));
    w = y; // assignment operator of weak_ptr takes a shared_ptr
    std::shared_ptr<int> x = w.lock();   // "promoted" shared_ptr

    std::cout << *x << " " << w.expired() << std::endl;
  }
  std::cout << w.expired() << std::endl;
  w.lock();   // returns a nullptr

  return EXIT_SUCCESS;
}
```



Summary of Smart Pointers

- A `shared_ptr` utilizes *reference counting* for multiple owners of an object in memory
  - `delete`s an object once its reference count reaches zero
- A `weak_ptr` works with a shared object but doesn't affect the reference count
  - Can't actually be dereferenced, but can check if the object still exists and can get a `shared_ptr` from the `weak_ptr` if it does
- A `unique_ptr` ***takes ownership*** of a pointer
  - Cannot be copied, but can be moved

Some Important Smart Pointer Methods

Visit http://www.cplusplus.com/ for more information on these!

- `std::unique_ptr<T> U;`
  - `U.get()` Returns the raw pointer U is managing
  - `U.release()` U stops managing its raw pointer and returns the raw pointer
  - `U.reset(q)` U cleans up its raw pointer and takes ownership of q
- `std::shared_ptr<T> S;`
  - `S.get()` Returns the raw pointer S is managing
  - `S.use_count()` Returns the reference count
  - `S.unique()` Returns true iff S.use_count() == 1
- `std::weak_ptr<T> W;`
  - `W.lock()` Constructs a shared pointer based off of W and returns it
  - `W.use_count()` Returns the reference count
  - `W.expired()` Returns true iff W is expired (W.use_count() == 0)

BONUS SLIDES

Some details about sorting the owned data within a container of smart pointers.

These slides expand on material covered today but won't be needed for CSE333; however, they are relevant for general C++ smart pointer usage in STL containers.

Smart Pointers and "<"

- Smart pointers implement some comparison operators, including `operator<`
  - However, it doesn't invoke `operator<` on the pointed-to objects; instead, it just promises a stable, strict ordering (probably based on the pointer address, not the pointed-to-value)

- To use the **`sort`**`()` algorithm on a container like `vector`, you need to provide a comparison function

- To use a smart pointer in a sorted container like `map`, you need to provide a comparison function when you *declare* the container

`unique_ptr` and STL Sorting

uniquevecsort.cc

compare pointed-to values

```
using namespace std;
bool sortfunction(const unique_ptr<int> &x,
                  const unique_ptr<int> &y) { return *x < *y; }
void printfunction(unique_ptr<int> &x) { cout << *x << endl; }

int main(int argc, char **argv) {
  vector<unique_ptr<int> > vec;
  vec.push_back(unique_ptr<int>(new int(9)));
  vec.push_back(unique_ptr<int>(new int(5)));
  vec.push_back(unique_ptr<int>(new int(7)));

  // buggy: sorts based on the values of the ptrs
  sort(vec.begin(), vec.end());
  cout << "Sorted:" << endl;
  for_each(vec.begin(), vec.end(), &printfunction);

  // better: sorts based on the pointed-to values
  sort(vec.begin(), vec.end(), &sortfunction);
  cout << "Sorted:" << endl;
  for_each(vec.begin(), vec.end(), &printfunction);

  return EXIT_SUCCESS;
}
```

swapping for sort done via move semantics

`unique_ptr`, "<", and `maps`

- Similarly, you can use `unique_ptr`s as keys in a `map`
  - Reminder: a `map` internally stores keys in sorted order
    - Iterating through the `map` iterates through the keys in order
  - By default, "<" is used to enforce ordering
    - You must specify a comparator when *constructing* the `map` to get a meaningful sorted order using "<" of `unique_ptr`s

- Compare (the 3rd template) parameter:
  - "A binary predicate that takes two element *keys* as arguments and returns a `bool`. This can be a function pointer or a function object."
    - `bool fptr(T1& lhs, T1& rhs);` OR member function `bool operator() (const T1& lhs, const T1& rhs);`

unique_ptr and map Example

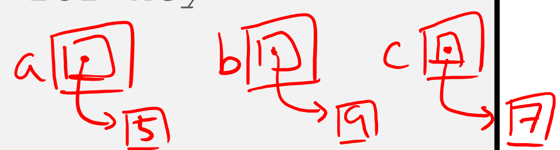
uniquemap.cc

still compares pointed-to values

```
struct MapComp {
  bool operator()(const unique_ptr<int> &lhs,
         const unique_ptr<int> &rhs) const { return *lhs < *rhs; }
};
```

// function object

```
int main(int argc, char **argv) {
  map<unique_ptr<int>, int, MapComp> a_map;  // Create the map

  unique_ptr<int> a(new int(5));  // unique_ptr for key
  unique_ptr<int> b(new int(9));
  unique_ptr<int> c(new int(7));

  a_map[std::move(a)] = 25;  // move semantics to get ownership
  a_map[std::move(b)] = 81;  // of unique_ptrs into the map.
  a_map[std::move(c)] = 49;  // a, b, c hold NULL after this.

  map<unique_ptr<int>,int>::iterator it;
  for (it = a_map.begin(); it != a_map.end(); it++) {
    std::cout << "key: " << *(it->first);
    std::cout << " value: " << it->second << std::endl;
  }
  return EXIT_SUCCESS;
}
```



move